An Overview of Building Diagnostics

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Introduction

Modern buildings are being designed with increasingly sophisticated energy management and control systems (EMCS) that have seemingly limitless capabilities for monitoring and controlling the conditions in buildings. Nonetheless, building heating, ventilating and air-conditioning (HVAC) equipment routinely fails to satisfy performance expectations envisioned at design. Furthermore, such failures often go unnoticed for extended periods of time.

How does this happen? There are a number of explanations. First, HVAC equipment is typically instrumented with the *minimum number of sensors* sufficient to implement basic local-loop and supervisory control strategies. Lack of sensor information is a significant barrier to assessing the operation of the equipment. A second explanation is that the *data that is collected overwhelms building operators* because there is little effort to consolidate the information into a clear and coherent picture of equipment status. Trend data from today's EMCS are useful, but only when analyzed by a human, and this is not a cost-effective way to continuously monitor system operation. A third explanation is that *building operators may overlook symptoms of a failure* because they may not fully understand the control strategies implemented. A related explanation is that *lack of understanding of sophisticated control strategies leads to manual overrides* that may temporarily alleviate a problem, but may lead to unintended and undetected operating problems in the future. Undoubtedly other explanations exist; however, there is little argument that there is vast room for improvement in the way buildings are monitored.

Given this set of barriers, what can be done to improve the performance of HVAC equipment? Webster's New Collegiate Dictionary defines diagnosis as it is used in this context as follows:

> ***Diagnosis:*** an investigation or analysis of the cause or nature of a condition, situation, or problem

Today's EMCS lack the tools necessary to 1) detect that problems (often referred to as faults) exist, and 2) assist building operators in diagnosing the problems that arise. This article provides an overview of building diagnostics. Included is a discussion of two fundamental types of diagnostics, motivating factors for the development of diagnostic tools, typical approaches to diagnostic reasoning, implementation strategies for diagnostic tools, the impact of diagnostic tools on primary stakeholders, and ongoing efforts to develop diagnostic applications.

Types of Diagnostics

The term building diagnostics can be used to describe investigations and analyses of problems with systems and equipment that are performed during commissioning and/or during everyday operations and monitoring. *Commissioning diagnostics generally use active test signals* to force valves, dampers, fans, etc. to a condition where the expected operation of the component or system is well understood. For instance, the economizer dampers of an air-handling unit could be commanded so that the outdoor air damper is wide open and the return air damper is closed. In this scenario, the mixed air temperature is expected to be nearly the same as the outdoor air temperature. If the two temperatures are significantly different, it could be that a sensor has failed or a damper is not functioning correctly. Passing this test does not ensure correct operation. The return air damper could be stuck closed and additional tests may be necessary to detect this problem. Such tests can be performed periodically throughout the life of the equipment; however, if possible they should be performed during unoccupied periods.

Monitoring diagnostics involves the passive assessment of components and systems and does not alter their operation. The same test described above could be performed passively by waiting for the air-handling unit to encounter driving conditions that forced the use of 100 percent outdoor air. The benefit of this approach is that it is nonintrusive. Its shortcoming is that it may be necessary to wait days, weeks or months before the air-handling unit experiences the conditions that allow this test to be performed. Hence, although some monitoring diagnostics are intended to operate continuously, the reality is that specific tests are only implemented when the conditions are appropriate.

Types of Diagnostics

- **Commissioning diagnostics –** uses active test signals to change the operation of a component or system to an operating condition that is well understood
- **Monitoring diagnostics –** passive assessment of system or component operation without altering operation

Benefits of Diagnostics

Having the capability to quickly diagnose operational problems in HVAC equipment means that equipment will operate as intended a higher percentage of the total run time. Some of the benefits of properly operating HVAC equipment are listed below:

Benefits of Building Diagnostics

- improved occupant comfort and health
- improved energy efficiency
- longer equipment life
- reduced maintenance costs
- reduced unscheduled equipment down time

One barrier to the widespread adoption of diagnostic tools is quantifying the impact of these benefits. This is not a trivial task. Its analogous to having regular checkups performed by your physician. There is no way to prove on a case by case basis that it will help you to live a longer and more enjoyable life, but on average and over time the benefits of regular care far outweigh the costs.

Approaches to Diagnostic Reasoning

Figure 1 provides a representation of the hierarchical structure of HVAC systems and subsystems in buildings and shows two approaches commonly used for diagnostic reasoning (IEA Annex 25, 1996). The first approach, termed the ***top-down approach***, uses performance measures from higher levels of the building/system/controller hierarchy to reason about possible lower-level causes of degradations to those higher level measures. For instance, whole building energy use is one high level measure that provides useful information about the performance of a building. If building energy use exceeds its expected value by an amount considered to be significant, top-down reasoning would be used to navigate down through the hierarchy and isolate the most probable explanations for the excess energy use.

The second approach, termed the ***bottom-up approach***, uses performance measures at lower levels of the hierarchy to isolate problems and then propagates that problem up through the hierarchy to determine its impact on building performance. If the impact is considered to be large or potentially large, correcting the problem would be given a high priority. If the impact is considered to be small, the decision may be to do nothing at this time. Performance measures at intermediate levels can be used in a top-down approach to isolate faults at lower levels, and also

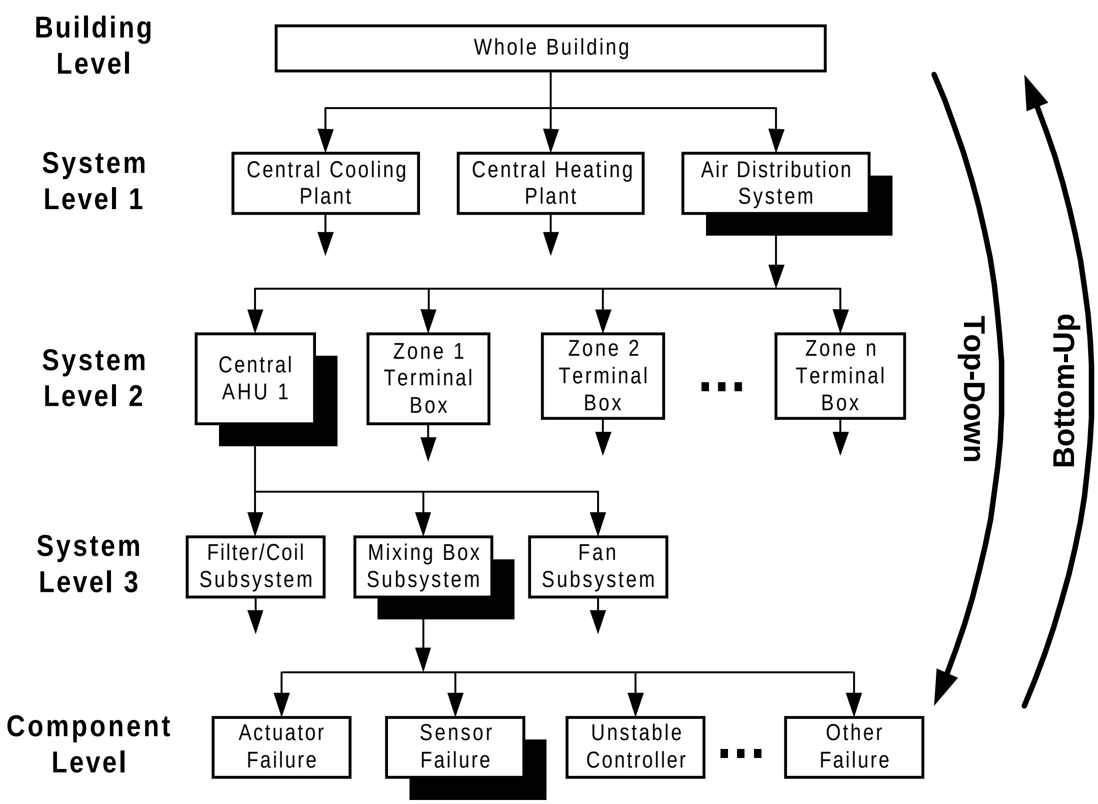

Figure 1: Top-down and bottom-up approaches to diagnostic reasoning.

in a bottom-up approach to determine the impact of the fault at the building level.

This discussion raises the important issue of how one determines when a performance measure exceeds or falls short of expectations. What is the basis for that expectation? In the case of building energy use it could be historical averages of monthly energy use. In other cases it could be expert knowledge. For instance, if the operation of a particular system violates one or more rules for normal operating behavior, the system fails to meet expectations. Expected values can also come from mathematical models based on physical laws or empirical data. Values predicted by the models can then be compared with actual measurements to assess performance. Figure 2 illustrates how the difference between the expected operation and actual operation can be used as the input to a classification technique whose output is a confidence that the given system is operating as expected. As the error between the expected and actual operation grows, the likelihood that the system is operating as expected diminishes.

Implementation of Diagnostic Tools

Early efforts at developing diagnostic tools have primarily focused on stand-alone implementations that run on personal computers and interface either directly to an EMCS, or to a database containing archived data. As diagnostic technology matures, stand-alone implementations will undoubtedly give way to implementations that are at least partially embedded in the control architecture. Figure 3 depicts a distributed control system of the future that includes diagnostic components (denoted FDD for fault detection and diagnostics) at various levels in the control hierarchy. The high-level air-handling unit (AHU) FDD tool identified in the figure could be a stand-alone module from an external service provider, or it could be an embedded module

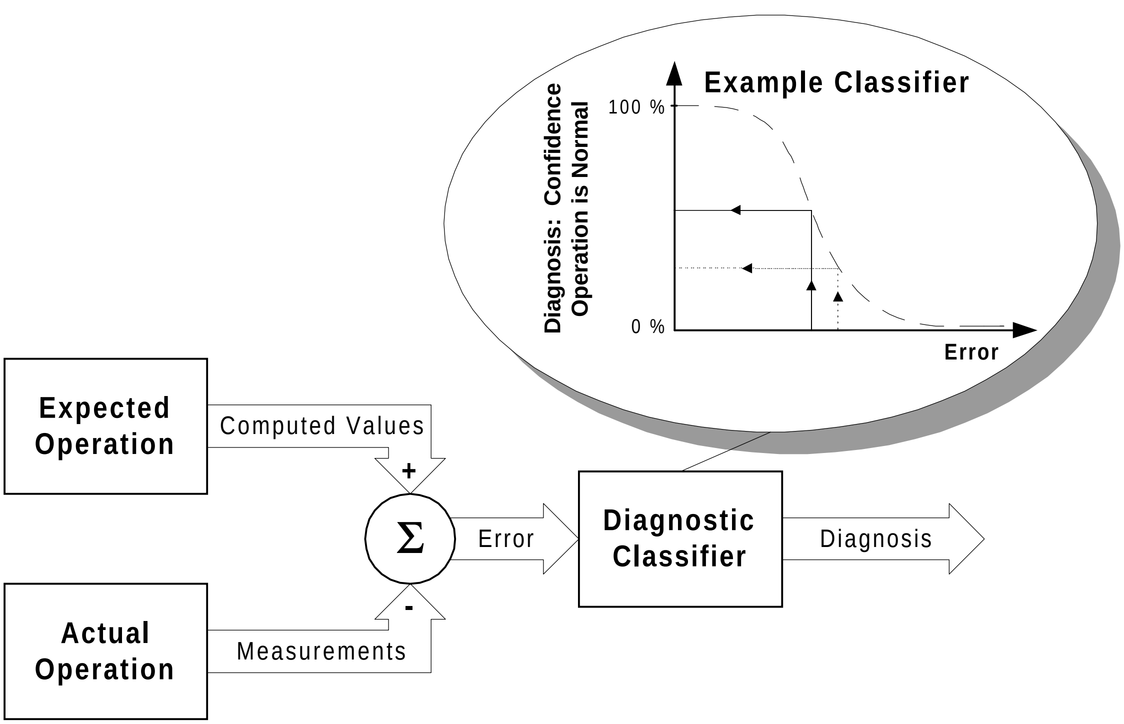

Figure 2: Illustration of a diagnostic process.

provided by controls manufacturers as part of their workstation software. Mid-level and low-level FDD tools shown in Figure 3 would likely be directly embedded in the supervisory and local controllers, although stand-alone implementations are also suitable in some cases. While Figure 3 represents a fully integrated and distributed FDD architecture, near-term expectations for the spread of the technology are more conservative. Early adopters of diagnostic tools will likely choose the prudent path of only implementing tools for a small number of systems or subsystems until they have greater experience with, and confidence in, the tools.

FDD tools residing at different levels in the distributed control system are primarily distinguished by the type of input data they utilize, the relative level of sophistication of their diagnostic algorithms, and the frequency at which the tools are invoked. More "intelligent" actions and knowledge would tend to be implemented at higher levels in the hierarchy where the available data has less detail. These higher-level tools might be implemented on a periodic basis such as once an hour, once a day, or once a week. At lower levels the actions require less reasoning because they are specific to a particular device. Here the data would be available on a nearly continuous basis and lower-level tools would tend to execute each time the data was updated.

As an example of a hierarchical implementation of diagnostic tools, models of HVAC equipment and simple tools such as routines for computing averages would likely reside at lower levels in a distributed control system because the detailed data necessary for these computations resides

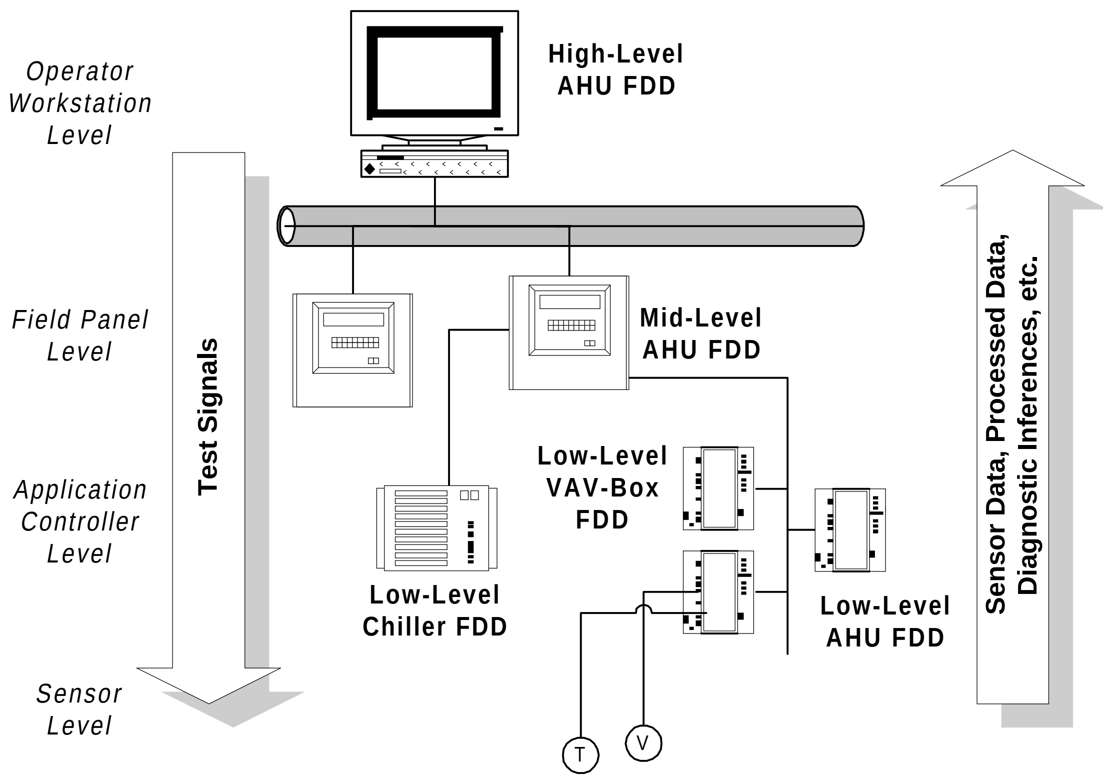

Figure 3: Distributed control system architecture depicting information flow in a hierarchical FDD architecture.

there. At higher levels, a rule-based method might use the averages obtained from various lower level controllers to reason about the operational state of the equipment. Figure 3 shows the flow of information propagating up through the hierarchical FDD architecture from the lower-level to higher-level FDD tools. Figure 3 also shows that higher-level FDD tools may have sufficient intelligence to inject test signals to lower-level controllers in order to determine the response of particular subsystems or components under more controlled conditions. As noted in a previous section, this type of procedure might be used during periodic recommissioning of a system. The hierarchical structure depicted in Figure 3 could also be expanded to multiple buildings monitored from a central location.

Diagnostic Stakeholders

To expedite the adoption of diagnostic tools into the day-to-day operation of buildings, it is necessary to identify the stakeholders with an interest in seeing this happen and to clearly define the incentives that diagnostics offers to each. A list of stakeholders and associated incentives is provided below. The incentives are mainly the benefits of diagnostics that were identified in a previous section. From the stakeholder point of view, almost all of these benefits can be translated into an incentive of either increased revenue or reduced cost. The possible exception is the occupant, whose primary benefit is thermal comfort. The argument can be made that for many occupants comfort is closely tied to revenues/costs because of its impact on productivity.

Stakeholders - Incentives Offered by Building Diagnostics

- **Owners** – tenant retention through improved building operation including better comfort and indoor air quality; increased protection from indoor air quality litigation; lower costs due to higher energy efficiency and longer equipment life
- **Operators** – more efficient monitoring and maintenance of buildings including the capability to identify appropriate personnel and parts for a repair, thereby reducing number of trips necessary to complete a repair; more comprehensive monitoring made possible by algorithms that perform time consuming data analysis to assist operators; both incentives become even greater for remote monitoring of buildings with no operator
- **Occupants** – improved conditions in occupied zones leads to higher productivity and better attendance; energy efficient operation leads to lower energy bills
- **Service Companies** – new business opportunities for companies that will remotely monitor building operation and schedule maintenance
- **Utilities** – new business opportunity, and higher energy efficiency will reduce the need for power generation
- **Controls Manufacturers** – product differentiation
- **Equipment Manufacturers** – product differentiation

Diagnostics: Past, Present and Future

The evolution of building diagnostics has primarily taken place in the 1990's. In the early 90's, the International Energy Agency (IEA) endorsed the formation of the Annex 25 Collaborative Research Project on *Real Time Simulation of HVAC Systems for Building Optimization, Fault Detection and Diagnostics*. Annex 25 members from ten participating countries worked cooperatively to identify common faults for various types of HVAC systems, to develop methods for detecting and diagnosing the faults, and to test the methods using simulation data with embedded faults. A wide variety of FDD methods were investigated including methods utilizing physical models of HVAC systems and components, black-box models, and fuzzy models, and methods using classification techniques such as artificial neural networks and expert rules (IEA Annex 25, 1996; ASHRAE, 1996). In general, the methods proved successful in diagnosing the faults considered; however, the simulation data used to compare the methods were not sufficient to gain a true understanding of the inherent strengths and weaknesses of the methods or to assess how the methods will be implemented and perform in real buildings.

Following the completion of the working period for Annex 25 in 1996, the IEA endorsed the formation of the Annex 34 Collaborative Research Project on *Computer-Aided Evaluation of HVAC System Performance: the Practical Application of Fault Detection and Diagnosis Techniques in Real Buildings*. Annex 34 members have sought to work with manufacturers of EMCS, building owners and operators, and consultants to implement and test in real buildings the FDD methods developed in Annex 25. To date, a number of small-scale demonstrations of FDD technology have been performed using data from real buildings.

In the past several years ASHRAE has also been active in sponsoring research in the area of FDD of HVAC systems. ASHRAE research specifically aimed at diagnostics includes:

- 883-RP Small Scale On-Line Diagnostics for an HVAC System
- 1020-RP Demonstration of Fault Detection and Diagnostic Methods in a Real Building
- 1043-RP Fault Detection and Diagnostic (FDD) Requirements and Evaluation Tools for Chillers

The efforts described above and others have produced prototype diagnostic tools for the following systems and subsystems:

Existing Diagnostic Tool Applications

- whole building systems
- chillers
- rooftop units
- air-handling units
- variable-air-volume boxes

Each tool is stand-alone in the sense that it does not make use of information provided by other diagnostic tools. Further descriptions of the diagnostic tools and the underlying methods implemented in these tools are provided in companion articles. The prototype tools have been tested predominantly with simulation and/or laboratory data and extensive field testing must still be carried out.

In the future, today's stand-alone prototype diagnostic tools will become a standard component of building operation. Diagnostics will either be embedded in the control system hierarchy (likely approach for tools developed by controls manufacturers) or provided as stand-alone modules that interface to the EMCS using an open communication protocol such as BACnet™ (likely approach for tools developed by external service providers). In either case, as the technology matures, diagnostic information obtained from tools for various systems and subsystems will begin to be integrated to form a comprehensive picture of the operational status of an entire building or group of buildings.

Acknowledgments

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